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Review

The impact of climate variability and change on the energy system: A systematic scoping review☆

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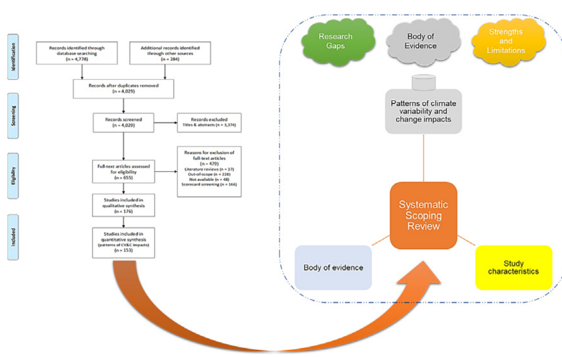
HIGHLIGHTS

- We applied a systematic scoping review based on Joanna Briggs Institute.
- We found evidence of consistent increase in global energy demand.
- Consistent decrease was found in Northern and Eastern Europe.
- Evidence of consistent decrease in thermoelectric output globally
- Solar PV showed a robust consistent pattern of increase in almost all regions.

GRAPHICAL ABSTRACT



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ABSTRACT

The energy system is a vital infrastructure which can be vulnerable to climate variability and change (CV&C) impacts. Understanding the impacts can prevent disruption and inform policy decision making. This study applied a scoping review in a systematic manner following the Joanna Briggs Institute guidelines to identify consistent patterns of CV&C impacts on the energy system, map and locate research gaps in the literature. A total of 176 studies were identified as eligible for inclusion in the review. This study found evidence of consistent increase in energy demand for Africa, the Americas and Asian continent. Consistent decrease was found in Northern and Eastern Europe, while increase in residential demand was projected in Oceania. There was evidence of consistent decrease in thermal power plant output globally. Solar photovoltaic showed a robust consistent pattern of increase in the Caribbean and Central America, Northern and Southern Africa and Oceania. As the global climate is changing in a future that is highly uncertain, the energy system should also evolve in order to adapt to the changing climate. Future impact assessment must integrate the impact of CV&C on power demand and supply while consider socioeconomic dynamics, cross-sectoral linkages and back-loops in a complete energy system model.

Abbreviations: CV&C, Climate variability and change; IPCC, Intergovernmental Panel on Climate Change; GHGs, Greenhouse gases; CCS, Carbon capture and storage; CCU, Carbon capture and use; CO_2, Carbon dioxide; GCM, General circulation models; NC, Near-century; MC, Mid-century; NC-MC, near to mid-century; EC, End of the 21st century; PV, Photovoltaic; IAM, Impact assessment models; MLR, Multiple linear regression; POLES, The Prospective Outlook for Long-term Energy Systems; GEMINI-E3, General Equilibrium Model of International-National Interactions between Economy, Energy and Environment; GEOTRANSF, A continuous non-linear hydrological model; NAM, Danish: Nedbør-Afstrømnings-Model; SWAT, Soil and Water Assessment Tool; MIKE SHE, System Hydrological European; TOPKAPI, TOPographic Kinematic APproximation and Integration; LEAP-WEAP, Long-range Energy Alternatives Planning System (LEAP) and Water Evaluation and Planning System (WEAP); T&D, Transmission and distribution; USA, United States of America; HVAC, Heating, ventilation and air conditioning system.

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Contents

1. Introduction

On October 8, 2018, the Intergovernmental Panel on Climate Change (IPCC) released a special report, Global Warming of 1.5 °C (IPCC, 2018). The report highlighted the need to reduce greenhouse gases (GHGs) to net zero in the next 12 years to have a reasonable chance of limiting global warming to 1.5 °C. The climate scientists warn that even half degree above will significantly increase the risks of frequent and intense drought, floods, extreme heat and poverty to millions of people. The global temperature has warmed by 1 °C since preindustrial periods and the IPCC reports suggest cutting emissions by 45% in 2030 and 100% in 2050, to prevent the earth from warming above 1.5 °C (IPCC, 2018). This implies that 70–85% of electricity should be sourced from renewables, putting a price on GHG emission and using technologies such as carbon capture and storage (CCS) to limit the accumulation of carbon dioxide (CO_2) in the atmosphere.

Besides the IPCC report, renewable energy system has been highlighted in most studies as a solution to mitigate climate change and provide an economic means of electricity generation. Some recent stdueis such as Teske (2019) show that it is possible to keep the earth below the 1.5 °C limit by transitioning to a 100% renewable energy system, engage in a major land conservation and restoration effort by mid-century. Another study by Bogdanov et al. (2019) suggest that a 100% carbon neutral renewable-based electricity system is possible by 2050 and economically feasible with solar and wind energy as the main source of electricity of about 70% and 18%, respectively. These studies among others, consolidates the move of scientific insights towards highly renewable energy systems.

In recent times, there have been some questions arising on the application of CCS as part of the solution space on climate change mitigation. Most outdated integrated assessment models have been found to be biased and strongly push for fossil fuel CCS, which is found by real state of the art research as highly questionable. This is because all renewable energy technologies simply cost less on a higher sustainability basis and lower cost basis. Therefore, industrial CCS application can be avoided. Some CCS parts may be switched to carbon capture and use (CCU), where the captured CO_2 can potentially be used for the manufacturing of fuels, carbonates, polymers and chemicals. Some current studies (Breyer et al., 2018; Breyer et al., 2017; Creutzig et al., 2017; Jacobson et al., 2018a; Jacobson et al., 2018b; Pursiheimo et al., 2018) show that fossil CCS is a solution of the past and no longer required in real progressive energy system modelling. Besides, CCS technology doubles the cost of power production which may be passed to the final consumers (İşlegen and Reichelstein, 2011). Therefore, the sustainability of the energy system and a progressive future under climatic conditions may require a more critical position for fossil CCS in mitigating global warming.

Global warming or climate change refers to the rise in average surface temperatures on the earth surface over a long period of time. Similarly, climate variability describes the way climate elements such as temperature and precipitation deviate from its average value in given months, seasons, years, decades or even centuries (Australia, 2018). Mitigating climate variability and change (CV&C) and its impacts will require the progressive decline of GHGs from 2030 to 2050 as suggested by the IPCC report. However, the reversal has been the case as the evolution of atmospheric CO_2 has been increasing and has reached an unprecedented high of ~410 ppm (ppm) (CO2.Earth, 2019). Climate models such as the general circulation models (GCMs) developed in the 1950s are valuable tools for quantitative understanding of climate dynamics and forecasting of future climate change (Edwards, 2011; Weart, 2010). The GCM projections are also used to understand the impacts of CV&C on human society and infrastructure.

The energy system is an important human infrastructure which is define by the IPCC as “all components related to the production, conversion, delivery and use of energy” (Intergovernmental Panel on Climate Change, 2015). Understanding the impacts of CV&C on energy systems is increasingly important for energy consumers, energy supply companies and policymakers. This is because CV&C may affect consumers through expenditures on energy commodities, companies through higher fuel consumption and emissions, and policymakers who struggle to make policies limiting global warming and ensuring energy security. The energy system is an important infrastructure in many countries and disruption can have serious economic implications.

Several studies have examined the impacts of CV&C on the energy sector and these studies include empirical[1] based studies and literature review-based studies. Empirical based studies apply a series of impact assessment models to explore the pattern of CV&C impacts on energy demand and supply. For example, Rey-Hernández et al. (2018); Wang et al. (2017) identified patterns of CV&C impacts in buildings, while François et al. (2018); Tobin et al. (2018); Zhou et al. (2018) examined the vulnerability of energy generating technologies to CV&C impacts. Literature review-based studies surveys the literature to identify state-of-the art in CV&C impacts. For example, Yau and Pean (2011) Li et al. (2012) Auffhammer and Mansur (2014) Ranson et al. (2014) Schaefli (2015) reviewed the literature on CV&C impacts on energy demand in buildings, Pryor and Barthelmie (2013) surveyed the literature on CV&C impacts on wind energy, Lumbroso et al. (2015) Sample et al. (2015) Schaefli (2015) Pokhrel et al. (2018) Shu et al. (2018) focused on hydropower studies, while Schaeffer et al. (2012) Chandramowli and Felder (2014) Ciscar and Dowling (2014) reviewed studies on CV&C impacts on energy demand and supply.

As empirical studies investigating CV&C impacts continues to expand, literature reviews have increased, applying methods ranging from narrative to systematic review. Systematic review approach is used to collate, evaluate and interpret results and it has been the least applied review method in the literature. Limited studies include Bonjean Stanton et al. (2016) who applied a systematic review to collate consistent patterns of impacts of CV&C on electrical supply systems in Europe, while Cronin et al. (2018) used a semi-systematic review to assess the trends of CV&C impacts on energy supply system. This study builds on Bonjean Stanton et al. (2016) and Cronin et al. (2018) but extends the studies to identify consistent pattern of CV&C impacts on the energy system at the global level. A systematic scoping review was applied to map the literature and identify consistent pattern of CV&C impacts on future energy system based on a broad range of robust evidence. By mapping the literature, this study identifies proximity and connections in terms of CV&C impacts at the regional and country-level and geographical distribution of studies and methods applied in general. Therefore, this study fits into the landscape of previous literature review on CV&C impacts of the energy system and applies a scoping review in a systematic manner.

Scoping review has been well applied in the field of health sciences. In general, the term scoping reviews means to '*map rapidly*' the key concepts underpinning a research area, main source and type of evidence available, and can be conducted as a stand-alone review, especially when a complex area has not been comprehensively reviewed (Wilson et al., 2012). A scoping review can be undertaken to systematically search, identify and map the literature. Examples of studies applying systematic scoping reviews in the health sciences includes Bonjean Stanton et al. (2016); Chambers et al. (2012); Conklin et al. (2015); Olariu et al. (2018). Besides Freiberg et al. (2018) who systematically scoped the literature to identify the health effects of people living near biomass power plants, the authors of this study are not aware of any scoping review on CV&C impacts on future energy system.

This study contributes to the growing literature by identifying consistent pattern of CV&C impacts at the global level using robust approach and mapped the literature to identify connections between future energy system and their vulnerability to climate change. The contributions of this study would be useful to advice energy companies and policymakers on planning for the future energy system considering future climate conditions. The rest of this paper is arranged as follows. Section 2 describes the methods applied in the systematic scoping review. Section 3 presents the study characteristics of the literature review and patterns of CV&C impacts. The discussion is presented in Section 4 which includes summary of the body of evidence, gaps in the literature review, and strength and limitations of the systematic scoping review. Section 5 concludes the study.

2. Methods

The methodology for this systematic scoping review is based on the Joanna Briggs Institute guidelines on conducting systematic scoping reviews (Arksey and O'Malley, 2005; Levac et al., 2010; Peters et al., 2015). The methodology summarises the evidence available on a topic in order to convey the breadth and depth of that topic (Olariu et al., 2018). The review was conducted in the following five key steps: (i) identifying the research question, (ii) identifying relevant studies, (iii) study selection, (iv) charting the data, and (v) collating, summarising and reporting the results. In this study, the scoping review is used to systematically map the literature, identify key concepts in the research, types and sources of evidence to inform policymaking and research (Wilson et al., 2012). The protocol used in this study was not registered as PROSPERO[2] currently does not accept systematic scoping review protocols and reviews that is not health related. The PRISMA[3] checklist for this paper is presented as Supplementary File 1.

2.1. Research question

This review is guided by the question, '*What are the characteristics, breadth and results of existing research conducted on the impact of CV&C on the future energy system*?

2.2. Identification of relevant studies

The literature search aimed to systematically identify peer-reviewed literature on the evidence of CV&C impacts on the energy system. The initial search was implemented on September 3, 2018, in two electronic databases: Scopus (includes records from 1960 to date) and Web of Science (records from 1965 to date). The databases were selected to be comprehensive and cover a broad range of disciplines. The search query consists of terms considered by the authors to be relevant words related to climate variability and change, impacts and vulnerability, and energy or power. Searches were limited to English language articles published between January 1990 and September 2018. The search was limited to articles from 1990 to conform with the IPCC First Assessment Report which was published in 1990 (Houghton et al., 1990).

The search string shown in Table 1 was applied to Scopus and Web of Science databases which returned 4193 and 1892 articles, respectively. The literature search was extended to Google search engine and Google Scholar to identify peer-review articles from journals that might not be indexed in the two databases. The search returned a total of 284 articles which were added to the results from the two databases. The final search approach adopted a 'snowball' technique in which citations within articles were manually searched if they appeared relevant to the review and included in this review (Wohlin, 2014). All citations were imported into the Endnote (Reuters, 2013) reference management software which was used to manage bibliographies and references used in this review.

2.3. Study selection process

Prior to the article selection process, duplicates and irrelevant papers were removed. The authors independently reviewed and applied selection criteria to the titles and abstracts. The initial selection was broad to accommodate any literature related to CV&C impacts on energy

[1] Empirical based studies are classified as original research, which differ from systematic reviews. Empirical studies described here includes studies that apply both statistical techniques such as econometric models, engineering simulation models, computable general equilibrium model, and life cycle assessment, and other related methods.

[2] PROSPERO is an international database of prospectively registered systematic reviews in health and social care. See https://www.crd.york.ac.uk/prospero

[3] Preferred Reporting Items for Systematic Reviews and Meta-Analyses. See http://www.prisma-statement.org

Table 1
Search query used to retrieve articles for the review.

Query	Scopus (200–2018) TITLE-ABS-KEY	Web of Science (2000–2018) Topic
"Climat* change*" AND "impact" AND "*energy*" AND "*lectric*" AND "*power*"	1416	603
"Climat* change*" AND "variability" AND "*energy*" AND "*lectric*" AND "*power*"	94	68
"Climat* change*" AND "?ffect*" AND "*energy*" AND "*lectric*" AND "*power*"	1753	878
"*temperature* change" AND "impact*" AND "*energy*" AND "*lectric*" AND "*power*"	42	15
"*temperature* change" AND "?ffect*" AND "*energy*" AND "*lectric*" AND "*power*"	195	56
"*weather* conditions*" AND "?ffect*" AND "*energy*" AND "*lectric*" AND "*power*"	500	182
"*weather* conditions*" AND "*impact*" AND "*energy*" AND "*lectric*" AND "*power*"	193	90
Total	4193	1892

systems. After reviewing the broad range of articles based on their titles and abstracts, the criteria were narrowed to only include studies focusing on the impacts of CV&C on energy systems in the near-, medium- and long-term (in this study, we use 'century' instead of '-term'). During the reviewing process, the references were tagged as 'literature reviews', 'out-of-study scope' and 'not available' for references that could not be retrieved as the documents were not available. The tagged references were used to store excluded studies that did not meet the eligibility criteria. Following Bonjean Stanton et al. (2016); Porter et al. (2014), a scorecard was developed to screen articles and ensure results (or projections) were suitable for inclusion in this review. The scorecard rated articles using star screening approach.

The score card contains attributes which includes the study approach, methodology, results and analysis and policy implication. The attributes of the scorecard are presented in Table S2a in Supplementary File 2. A five-star article clearly describes the study approach that is appropriate for the impact assessment with a balance description of applied methodology and results obtained, states limitations and presents policy implication. A Four-star article assumes the attributes of a five-star article but detailed information of the GCMs, results comparison with previous studies and model limitation were not included. Three-star article includes the attributes of four start article but a clear description of number of GCMs, scenarios and impact models, the use of the results for planning and implications are not presented. Articles below three stars provided little information on impact assessment methods and parameters, and results from such studies were not reliable enough to be considered for this review. Throughout the screening process, the reviewers met regularly to resolve conflicts and discuss any issue related to articles selected for this review (Levac et al., 2010).

2.4. Charting the data

After the study selection process, there were 176 articles scoring between three to five stars with publication dates ranging from 1992 to 2018. Fig. 1 shows the evolution of studies included for this review and 2016 can be observed to be the year with higher number of publications.

The studies included were used to develop a charting table to record qualitative information of the authors, study location, aim, assessment method, results and limitations. The qualitative information from studies included were used to identify projected impacts of CV&C on the energy system for the future period assessed, and to examine the consistent or inconsistent nature of the results. Here, higher number of consistent results implies a more robust pattern of CV&C impacts for the energy system. The approach identified 153 studies which were used for quantitative synthesis to identify the pattern of CV&C

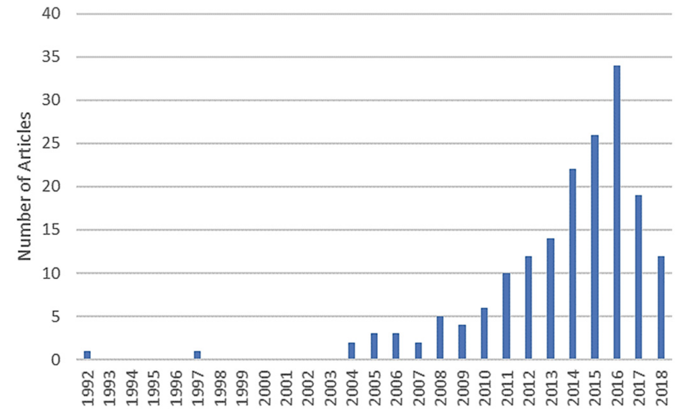

Fig. 1. Article included in the review by publication year.

impacts on energy demand and energy technologies (labelled #1–153 in Table S2b in Supplementary File 2). The quality (risk of bias) of three to five-star studies were independently assessed by the authors.

The 153 studies produced 1790 individual results for patterns of CV&C at regional and country level. The pattern of impacts was either increase, decrease or no change and the assessment periods were for the near (present to 2039 or 2030s), medium- (2040 to 2069, or 2050s) and end-century (2070 to 2099, or 2080s). However, the heterogeneity of the assessment periods used in the studies made it challenging to present an overall result. Therefore, the results were re-mapped into two assessment periods, near to mid-century (NC-MC) and end of the 21st century (EC). The results of the near-, mid-, and end-century are available sheet in the Excel Supplementary Material, while the NC-MC and EC results for the regional and country level are available in sheet 2 (Excel file) in Supplementary File 3.

In terms of the pattern of impact, an increase in the demand sector means an increase in energy demand in a future period, while an increase in energy technologies such as thermal, hydropower, solar photovoltaic (PV), etc., means an increase in production due to the impacts of CV&C. Results for 'commercial' includes schools, hospitals, supermarket, hotels, and other public facilities. Results for 'buildings' are for studies that analysed energy demand at an aggregate scale (e.g. country level energy demand) or total building energy demand in a location. Results for impact assessment on energy technologies where combined with assessment from their respective energy resources. For example, impact assessment on wind turbines are combined with assessment on wind resources such as wind speed, while assessment on hydropower was grouped with assessment on water resources, etc. Finally, two or more studies with conflicting results for impact pattern for an energy technology or energy demand was termed 'inconsistent' as the direction of impact could not be determined.

2.5. Collating, summarising and reporting the results

Based on the study findings, results are presented to describe the characteristics features of the study which includes the geographical distribution, journal publication, sector/sources analysed, methods applied and pattern of CV&C impacts on the energy system. In line with a scoping review, a summary of the body of evidence is presented in Section 4, with the gaps in the literature and strengths and limitations of the systematic scoping review.

3. Results

The PRISMA flow diagram (Liberati et al., 2009) for this study is shown in Fig. 2. The literature search yielded a total of 5062 articles which was reduced to 4029 after the removal of duplicates. While screening the titles and abstracts, 3374 studies were excluded, and

655 studies were included for eligibility assessment. The included studies were screened, and 479 studies were further excluded which includes literature reviews (37), out-of-scope studies (228), articles with no documents available (48) and articles below three-star rating from the scorecard (166). After the eligibility screening, 176 studies were included for qualitative synthesis out of which 153 studies were used for the final quantitative synthesis where the patterns of CV&C impacts were identified.

3.1. Study characteristics of the literature review

3.1.1. Geographical distribution

The geographical distribution of the studies by region, country and number of energy technologies analysed are show in Fig. 3. The studies by country as shown in panel A of Fig. 3 indicates that most of the published literature on the impact of CV&C on the energy system have improved with studies found in developing countries in Africa and the Asian regions. However, the most studies conducted on the topic has been in the United States of America (USA) (45 articles), China and Germany (12 articles each), Australia and Brazil 11 and 10 articles, respectively. The studies by regions as shown in the left-hand side of panel A in Fig. 3 show that although studies focused on European regions tend to dominate the topic, studies in have become visible in northern, western and southern African regions. The studies included for the review were further scrutinised to examine the progress literature has made in investigating the impact of CV&C on energy technologies. This allowed for the identification of countries that were not captured in the panel A and the results are presented in panel B of Fig. 3. It is clearly observed that more countries were identified based on the number of technologies assessed for the vulnerability to climate change.

The most prominent energy technology was hydropower which were observed to have been investigated in almost all the developing countries. This is because the impact assessment was conducted at the catchment or river basin level which can cover various countries with hydropower plants. For example, the study by Pereira-Cardenal et al. (2014) investigated climate impact on the Iberian Peninsula which covers Spain and Portugal, and Popescu et al. (2014) study on climate impact on energy production in La Plate Basin which covers Brazil, Uruguay, Paraguay and part of Argentina. From panel B in Fig. 3, the countries with higher number of technologies assessed for climate impact are China and Finland (7 technologies each), Italy, Netherlands,

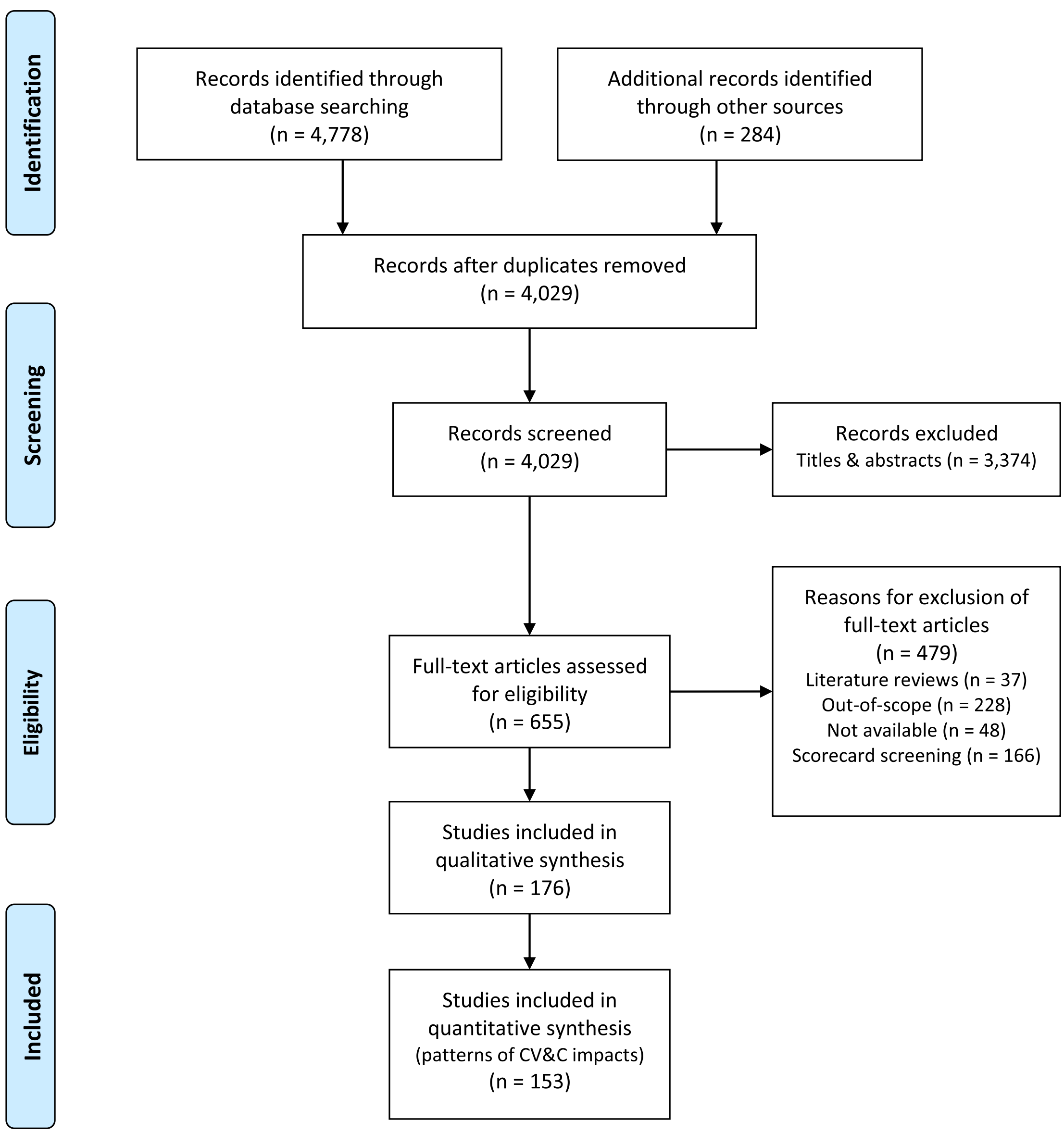

Fig. 2. PRISMA flow of studies in the systematic scoping review and reasons for exclusions.

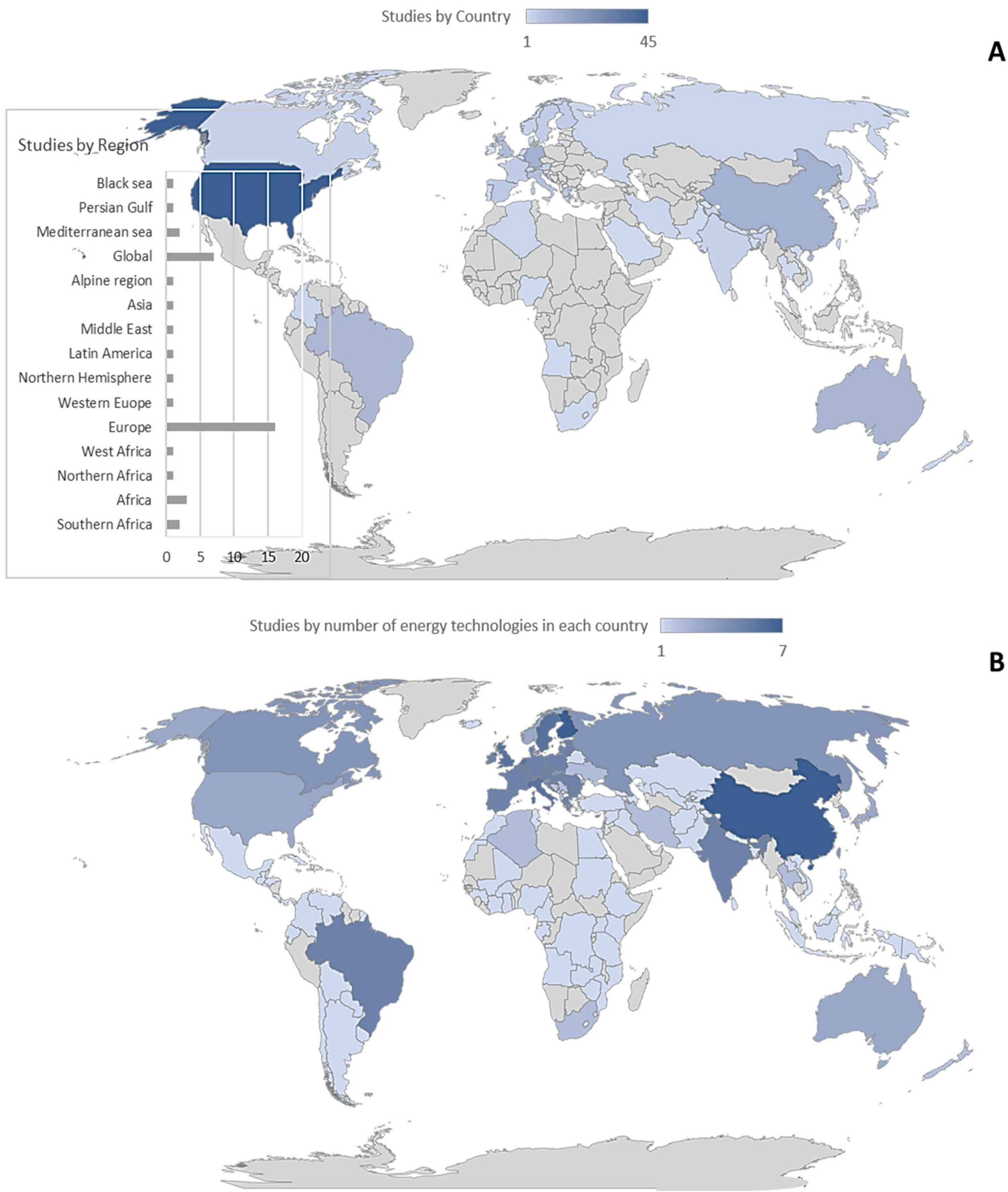

Fig. 3. Geographical location of studies selected for the review Note that Fig. 3A includes two results (i.e. Studies by Country and Studies by Region).

Sweden and the UK (6 technologies each). The results also show that fewer technologies have been assessed for their vulnerability to climate change in countries located in the African continent, South and Central America and the Asian continent (except Eastern Asia).

3.1.2. Journal publications

In this section, the studies included for the current review are analysed based on the articles per journal and journal publication by year. Panel A in Fig. 4 shows the results of article on the impact of CV&C on the energy system published in journals with >5 publications between 1990 and 2018. With >17 of the 176 total studies, *Climatic Change* has published more studies than any other journal. This is followed by *Energy*, *Renewable Energy*, *Energy and Buildings*, *Energy Policy* and *Applied Energy*. The top eight journals shown in panel A have published 51% (90 of the 176 papers) of the studies to date. The second group of journals with <5 publications were eighteen journals in total, representing 26% (45 of the 176 papers) of the studies to date with *Energy Conservation and Management*, *Energies* and *Journal of Hydrology* having 4 papers each during the study period. The last group of journals with 1 paper made up 23% (41 of the 176 papers).

The evolution of the journal publication by year are shown in panel C in Fig. 4 which also contains the list of journals not mentioned in panel A and B. As can be observed from panel C, *Climatic Change* had the most publication in 2012 and 2015 while *Energy and Buildings* and *Applied Energy* had 4 papers published in 2016 which was the highest for the year. However, *Renewable Energy* have maintained a 3 paper per year publication from 2016 to 2017. The influence of journals towards the papers published is greater when the sector or source assessed for climate impact are ideally the focus of the journal. For example, studies focusing on climate impact on building energy demand have been mostly published in *Energy and Buildings* and *Building and Environment* journals, while studies focused on addressing climate impact on renewables are mostly published in *Renewable Energy* journal. Climatic Change Journal appear to have greater influence on the topic due to its broad scope of examining issues of CV&C on the country, regional and global level.

3.1.3. Sectors/energy technologies analysed

The articles reviewed were diversified in terms of sectors/sources analysed for climate impact as shown in Fig. 5 which also shows the evolution of studies by publication year. The hydropower sector was clearly the most researched energy source for supply side studies with 8 papers per year from 2013 to 2015 which increased to 15 papers in 2016 and declined to 7 papers in 2017. Other energy sources include wind and thermal power plants with significant number of publications in 2015. On the demand side, the studies focusing on the impact of CV&C on energy demand in an economy had high number of studies published yearly and this may be due to data availability for conducting impact assessment at the aggregated level which is more readily available than disaggregated data for sectoral energy demand. Combining the sectors analysed and sorting them into energy demand, energy supply and electricity networks identifies sectors/energy sources with higher or lower research concentrations as shown in panel B of Fig. 5.

Energy supply studies is observed to make up 66% of the total number of studies, with hydropower accounting for 46% of the supply side studies. On the demand side, assessment of climate impact on economywide energy demand made up 44% of the studies reviewed, while residential and commercial sectors had 29% and 27%, respectively. The least researched climate impact on energy sources are ground source heat pump, transmission and distribution networks, wave energy and bioenergy which makes up between 1 and 2% of the total studies reviewed. This implies that during the period between 1990 and 2018, researchers have been more interested in examining the impact of CV&C on energy supply in general and hydropower in particular. This might be due to the vulnerability of the hydropower sector to climate change which can affect electricity supply as hydropower contributes about 71% of the total renewable electricity and 16.4% of the world's electricity generation by source (Council, 2016).

3.1.4. Methods applied

Over the years, a range of methods have been applied to assess the impact of CV&C on the energy system. They range from the less complex approach where GCM data are used as a proxy for climate impacts (e.g. Cradden et al. (2012), Carvalho et al. (2017)) to the more complex method where data from GCM are used as inputs to impact assessment models (e.g. POLES used in Dowling (2013b)) (IAM). The GCM data are retrieved from available climate change projection datasets (e.g. UKCP09 used in Braun et al. (2016)) and in some cases, combined with emission scenarios (e.g. Seljom et al. (2011), Majone et al. (2016)) or adjust the time series to a specific linear trend for the parameter (e.g. Koch et al. (2014)). GCM data used as input in IAM were

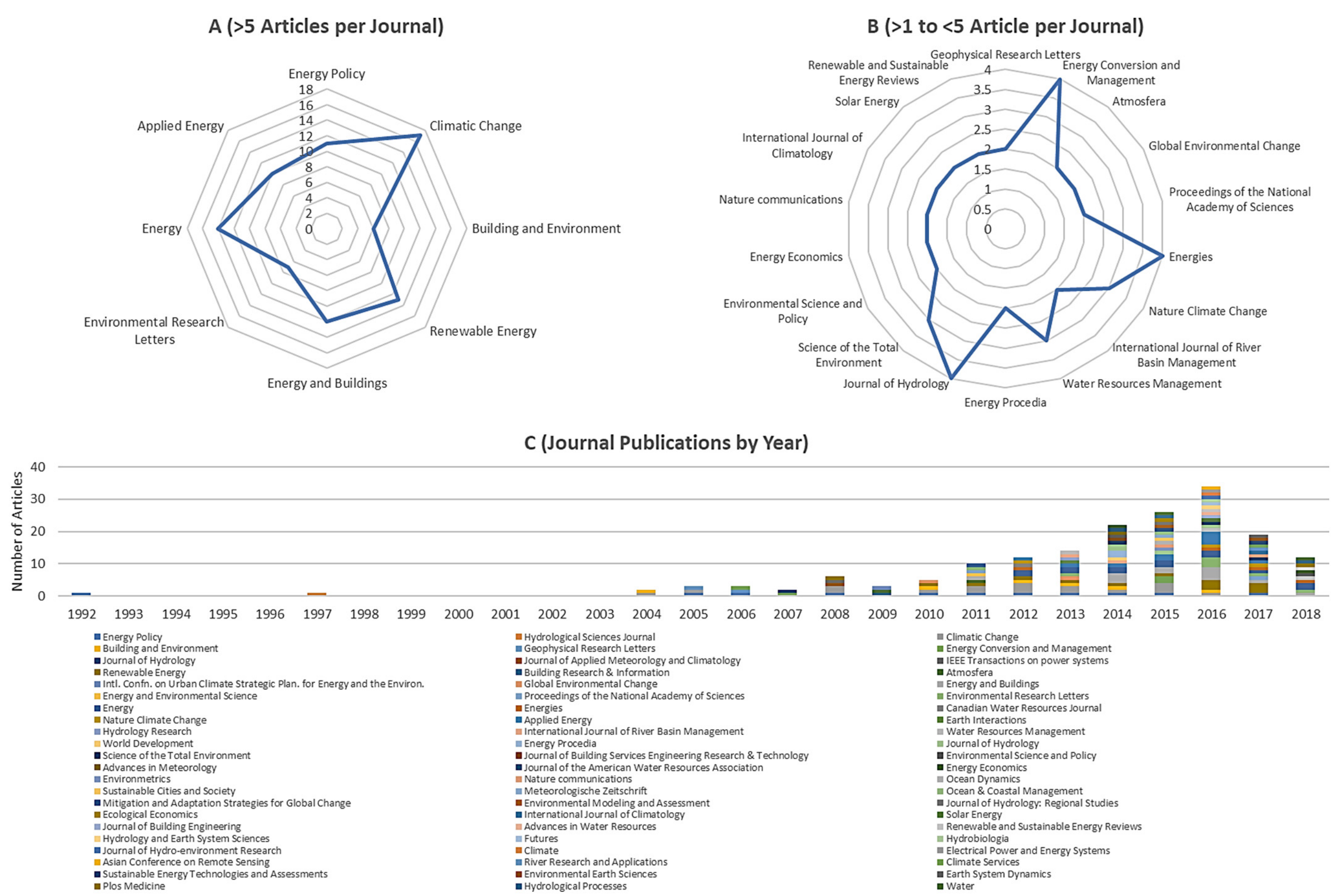

Fig. 4. Journal publications of the studies reviewed.

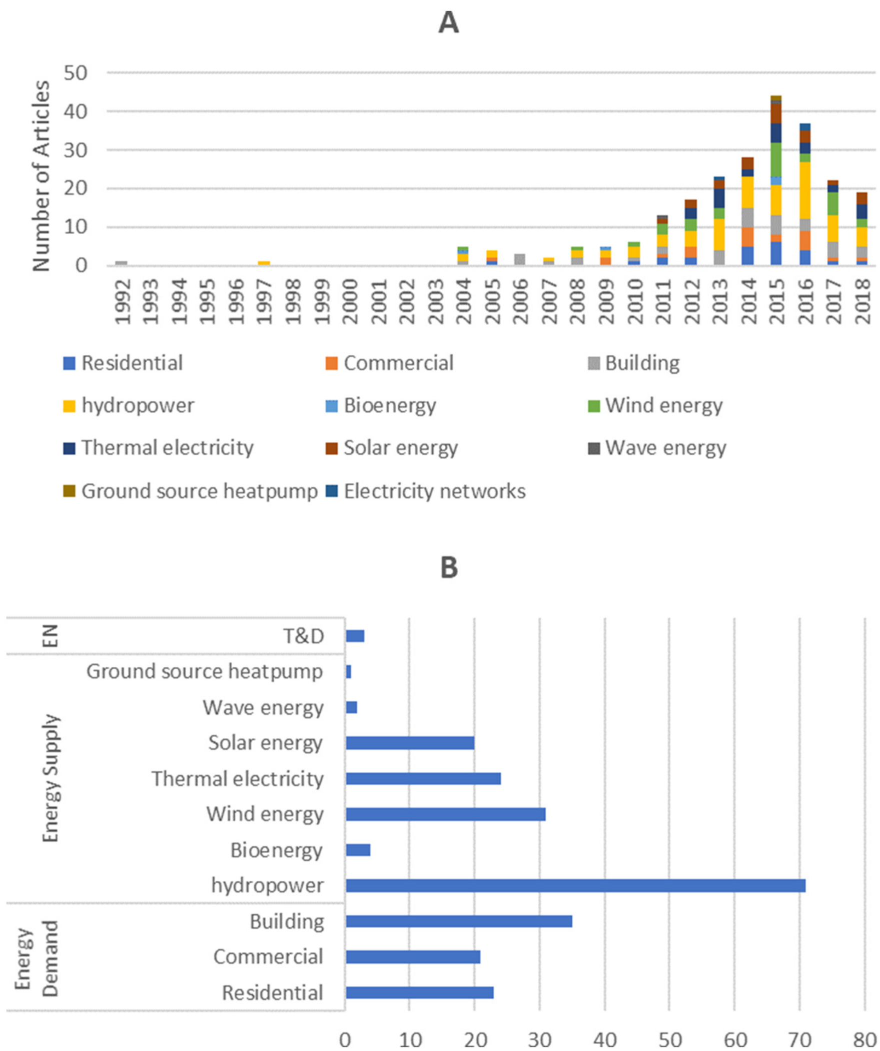

Fig. 5. Sectors/energy sources by year (A) and by the total number (B) (EN: electrical networks, T&D transmission and distribution).

measured by its distribution, mean and median and varied across the literature.

Built environment such as residential and commercial buildings use electricity for heating/cooling and powering other household appliances. Energy source such as gas and heating oil are mostly used for space heating in buildings. Based on the articles reviewed, the impact of CV&C on energy demand were assessed using multiple linear regression (MLR) and bottom-up energy models. A large amount of demand side studies applied MLR model where climate (e.g. temperature, precipitation) and economic (e.g. price, income) variables are independent variables are regressed with energy/electricity demand as dependent variables. The coefficients from the MLR model and climate projections are used to estimate changes in future energy demand compared to the base year. Examples of study applying MLR include Li et al. (2014) and Chen et al. (2016). Bottom-up energy simulation model are developed and used to predict future energy use in buildings. Climate data are retrieved from GCMs and integrated within the simulation model. Examples include IDA ICE building simulation software used in Waddicor et al. (2016) and EnergyPlus in Reyna and Chester (2017). Other studies used partial equilibrium model to estimate the impact of CV&C on the energy system (e.g. POLES[4] (Dowling, 2013a; Mima and Criqui, 2015) and GEMINI-E3[5] (Labriet et al., 2015)).

Electricity generation from hydropower facilities rely on the availability of water resources, seasonal patterns of the hydrological cycle, variation in water inflows, water storage capacity[6] and installed capacity of the power plants (Minville et al., 2009). Climate impact on hydropower production are estimated using hydrological models (e.g. GEOTRANSF[7] applied in Majone et al. (2016), NAM,[8] SWAT[9] and MIKE SHE[10] applied in Karlsson et al. (2016)) or simulation models used for electricity dispatch from hydropower plants (e.g. TOPKAPI[11] used in Maran et al. (2014)). According to Schaeffer et al. (2012), climate change can affect heating and cooling requirements of power plants operating under Rankine or thermodynamic and Brayton cycles and the effect may vary according to the average temperature, humidity, pressure and availability of water. Coal and nuclear power plants operate under the Rankine cycle and their thermal efficiencies are affected by changes in ambient temperatures (Linrterud et al., 2011). Gas power plants, such as open cycle- and combined cycle- gas or steam turbines, are based on Brayton cycles (Bahrami et al., 2015). The turbine power output, fuel consumption and efficiency of Brayton cycle power plants may be affected by increase in temperature and humidity. Hydrological models

[4] The Prospective Outlook for Long-term Energy Systems
[5] General Equilibrium Model of International-National Interactions between Economy, Energy and Environment

[6] With enough storage capacity in reservoirs associated with hydropower units, major fluctuations of precipitation from daily to annual scales can be adequately managed.
[7] GEOTRANSF: a continuous non-linear hydrological model
[8] Danish: Nedbør-Afstrømnings-Model
[9] Soil and Water Assessment Tool
[10] System Hydrological European
[11] TOPographic Kinematic APproximation and Integration

such as WaterGAP3 and SWIM have been applied to thermal electricity generation as well as regression models used in Linrterud et al. (2011) and LEAP-WEAP[12] model applied in Sun et al. (2018).

Wind speed significantly varies with height (Schaeffer et al., 2012), wind energy cannot easily be stored[13] and it is intermittent (Camacho et al., 2011). The impacts of CV&C are assessed by retrieving wind speed projections from GCM as a proxy for wind power production or by extrapolating wind speed for a particular height of the hub of the turbine model being assessed (Bonjean Stanton et al., 2016). Changes in temperature can affect efficiencies of solar PV cells leading to low power output (Skoplaki and Palyvos, 2009). In this study, the impacts are quantified as changes above or below 1% for energy demand sectors or energy supply technologies. The reviewed studies assessed CV&C impacts on solar PV by developing a model of PV power generation based on the change in global radiation and the averaging by distribution of orientations and tilt angles of PV modules within a region (Wachsmuth et al., 2012; Wachsmuth et al., 2013). For wave energy, methods used in assessing CV&C impacts includes WAVEWATCH III model (Reeve et al., 2011) and using future downscaled wind data to generate wave characteristics (Kamranzad et al., 2015). Transmission and distribution systems are prone to climate change impacts due to their long delivery distance, which may cause delivery failure of either electricity or energy resources. Some notable climate conditions that affect transmission and distribution systems are flooding, lightning strikes, heavy winds or ice loads, landslides and avalanches (Grigsby, 2016). The impact of CV&C on transmission and distribution infrastructure can be assessed from projections generated from Monte Carlo simulations Ryan et al. (2016).

3.2. Patterns of CV&C impacts

The reviewed studies described various patterns of CV&C impacts on energy demand and energy generating technology. This section identifies patterns of CV&C impacts and presents the results at the regional and country levels which are shown from Figs. 6–7. In the regional result, more than one result from two studies are included to improve the robustness of the patterns of CV&C impacts on sectors and energy technologies. Inconsistent results are highlighted in yellow colour for the regional (Figs. 6–8) and national (Figs. 9–10) results. In the country result, three level of colour dept. are used as a proxy for robust consistent pattern of CV&C impacts. The results are presented in more detail in Table 2 where the results from an article reviewed are coded for a specific region or country for an energy demand sector and energy generating technologies.

3.2.1. Regional level

The annual consistent patterns for CV&C impacts on residential, commercial, building energy demand, hydropower, wind, thermal, solar PV and wave energy on the regional level are shown in Figs. 6–8. This covers the five world regions (Americas, Africa, Asia, Oceania and Europe) and their respective sub-regions for the near-mid 21st century *(NC-MC)* and end of the 21st century *(EC)*. The results are analysed based on the sectors and energy technologies.

The results show great variations in pattern of energy demand across regions and time periods. More specifically, this study identifies consistent increase in energy demand for residential and commercial sectors in Southern Europe, the Americas and part of Asia, while decrease is observed in Oceania region, Central and East Asia, Northern and Western Europe. Building energy demand is projected to experience increase in demand in Africa, Asia, America and Oceania regions but decreasing in Northern and Eastern Europe. From a regional perspective, most individual results from articles showing a consistent pattern of increase or decrease in energy demand are projected to occur in the NC to MC. Also, inconsistent results were fewer compared to consistent results and only one region (Eastern Europe) showed no change in commercial energy demand by EC. This shows that the collective regional studies appear to agree that the effect of climate change on energy demand may occur more sooner than expected. This tends to be in line with the recent warnings by the IPCC (IPCC, 2018) on the imminent climate change which will have impacts such as extreme heat wave among other impacts.

On power supply technologies, no inconsistent results were identified in the pattern of climate change impacts on hydropower production. However, unlike the case of energy demand sectors, the results for the articles reviewed showed a balance between climate impact for the NC-MC and EC time periods. More studies tend to agree on the consistent increase in hydropower generation in Northern Europe which will be due to rise in precipitation as the rate of glacier melt increase as a result of global warming. The increase in precipitation will require an expansion or upgrade of hydropower facilities to accommodate the increase water runoffs and reduce losses due to water spillage. Hydropower production in other European regions are projected to decline in other European regions, Northern and Southern Africa, the Americas and part of Central and Western Asia.

Decrease in power output from thermal power plants were identified in the studies reviewed due to decreasing precipitation and higher temperatures which lead to a reduction in available cooling water for power plant operation. The regional results show that the European region, Western and Southern Africa, Western, Southern and Central Asia, North America and Oceania regions will experience reduction in thermal power plant generation. This review identified Eastern and Southeast Asia as the region expected to have higher thermal power generation under climate change conditions. The results of the review for solar PV systems were either increase or decrease in the consistent pattern of CV&C impacts. Although the impacts were mostly lower in term of percentage change (<3% impacts in most papers) when compared to thermal and hydropower production, increase in solar PV is projected for Southern Europe, Northern and Southern and Africa, Central America, Caribbean and Oceania. With CV&C impact on solar PV system <3% in most studies, the technology is practically not endangered in its relevance for the current and future energy system. Power generation for wind energy installations is projected to increase in Northern Europe, parts of the Mediterranean, Black and Baltic Seas and South Africa. No consistent or inconsistent pattern of impacts for regional results were identified for bioenergy production.

3.2.2. Country level

At the country level, annual patterns of CV&C impacts on energy demand sectors and energy generating technologies appear in Figs. 9 and 10. Each figure is divided into ten panels from the letter A-J for residential, commercial, building, hydropower, bioenergy, wind, thermal, solar PV, wave and transmission and distribution(T&D). The colour patterns are similar to the regional results which represents the level of robustness for each energy technologies. A close observation of the two figures reveal that panel A-D representing impacts of CV&C on residential, commercial, building and hydropower as the most researched areas in the literature compared to other areas of CV&C impact assessment on the energy system. Scanty literatures on the impacts of CV&C includes bioenergy, wind, thermal, solar PV, wave and T&D for the *NC-MC* and *EC* periods. It can be observed that more results from studies are available for the *NC-MC* than the *EC*, especially for developing countries in Africa and Asian continents.

Other inconsistent results (represented by yellow colour in the two figures) were found in the *NC-MC* results (Fig. 9) than the EC results (Fig. 10). This implies that *EC* projections are more consistent across GCMs than projections from *NC-EC*. However, it is important to note that the results were initially developed for the near, medium and end

[12] Long-range Energy Alternatives Planning System (LEAP) and Water Evaluation and Planning System (WEAP)

[13] Wind power require advanced control techniques in order to achieve high performance and reliable operations.

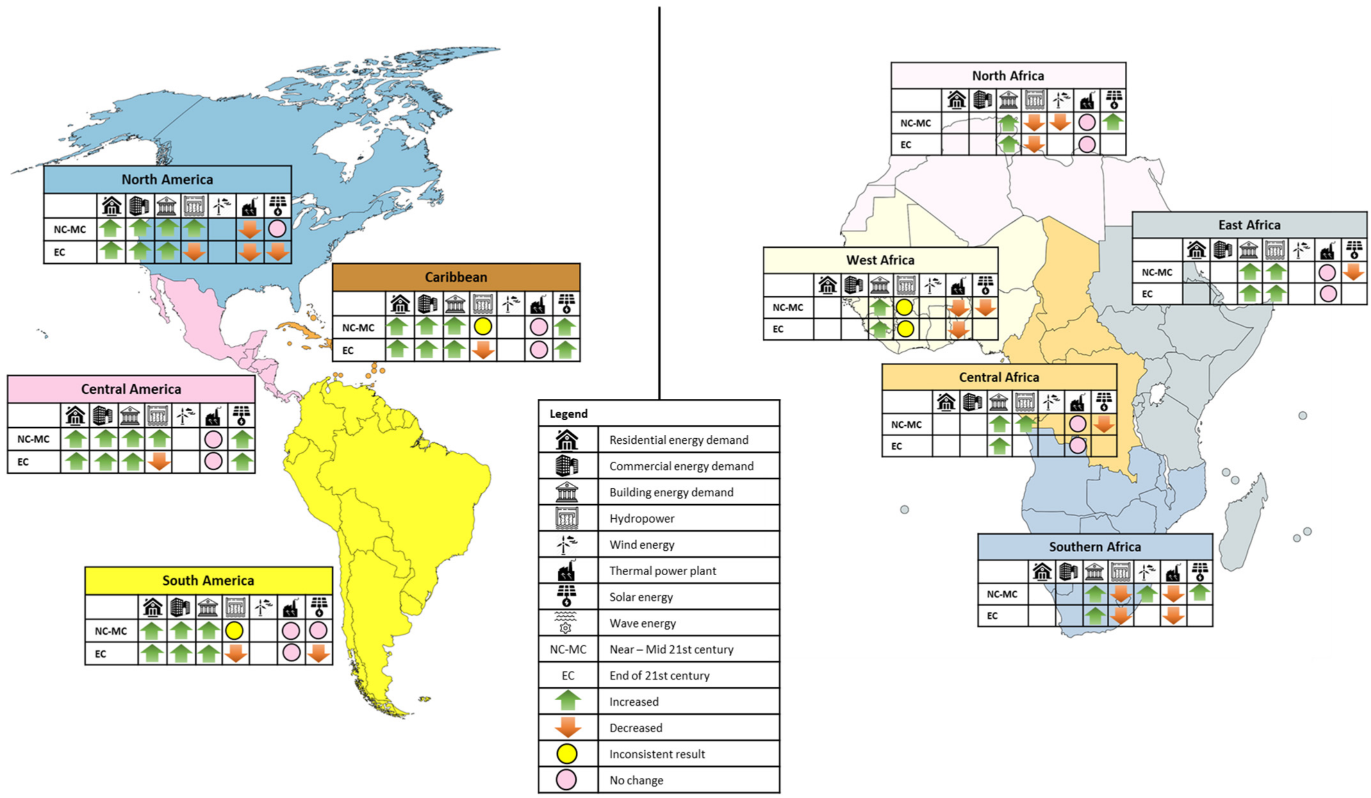

Fig. 6. Annual consistent patterns of impacts of CV&C on energy consuming sectors and technologies in the Americas and Africa (Icons retrieved from www.flaticon.com).

of the century, but the near and mid-century results were combined to form the *NC-MC*. The detailed results and their respective studies at the country level are presented in Excel file in the Supplementary File 3. Also, due to the large number of countries identified, the citation will not be mentioned but the number of results included for the country. The results for USA and Australia's state-level results are show in Fig. S2a–S2b in Supplementary File 2.

From the country-level energy demand results in Table 2, it can be clearly observed that more countries will experience an increase in energy demand due to global warming as compared to countries projected

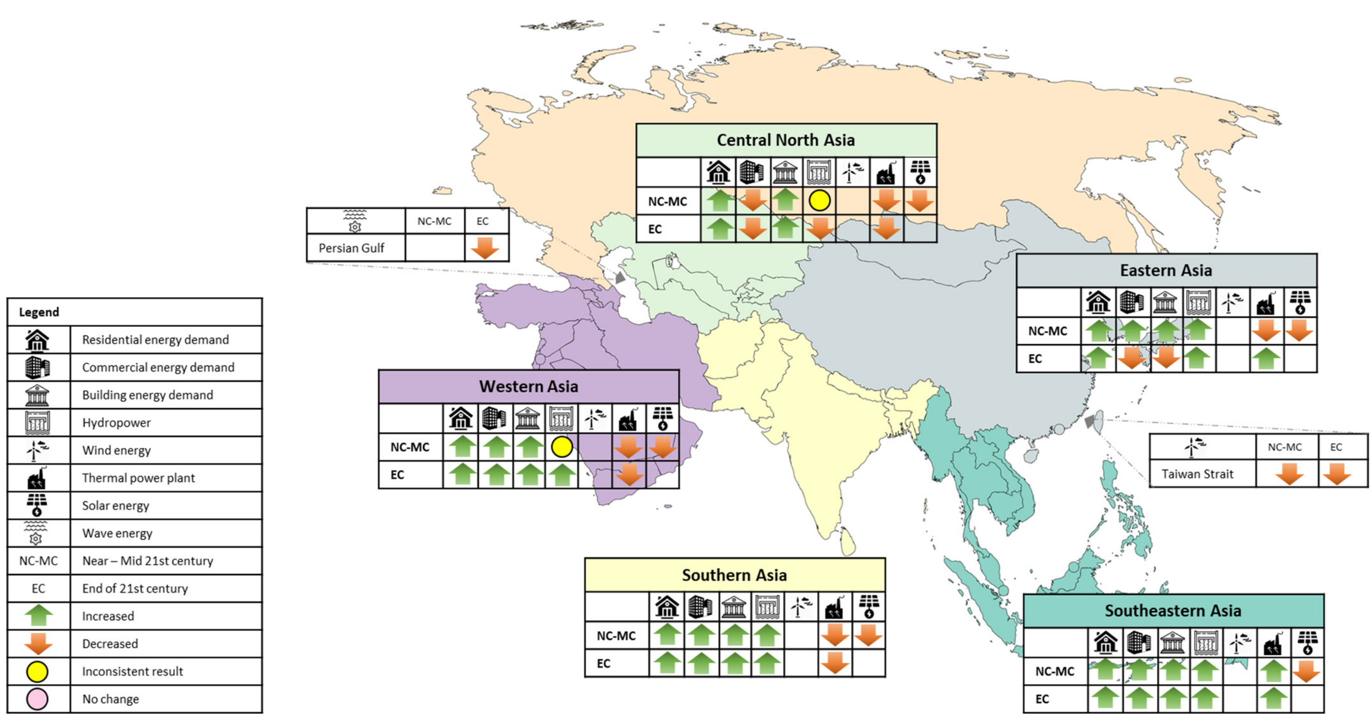

Fig. 7. Annual consistent patterns of impacts of CV&C on energy consuming sectors and technologies in Asia (Icons retrieved from www.flaticon.com).

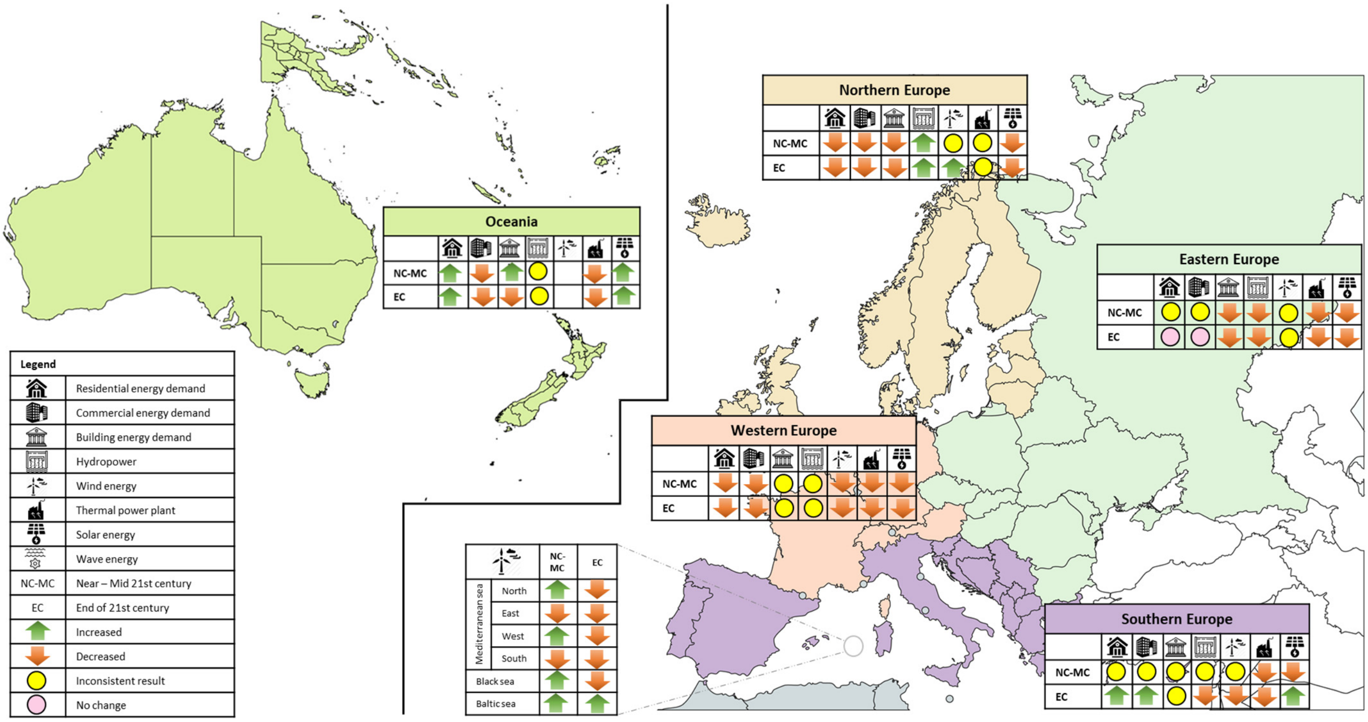

Fig. 8. Annual consistent patterns of impacts of CV&C on energy consuming sectors and technologies in Oceania and Europe (Icons retrieved from www.flaticon.com).

to have a decrease in energy demand. However, the consistent pattern of CV&C impacts will mostly occur during the MC and EC time periods as shown by individual results from the articles reviewed. This slightly differs from the regional results where most results showing consistent pattern of increase and decrease during the NC and MC time periods. This implies that if an average is taken for changes in energy demand across the regions and country-level results, the MC tend to have the most impact of projected changes in energy demand across the studies reviewed.

Unlike the regional results, the country-level results show that fewer countries will experience an increase in thermal power, solar PV and wind energy generation compared to countries projected to have a decline in power output from the energy technologies. The reviewed studies show that the decreases projected for thermal power plants are for once through cooling system (Tobin et al., 2018; Van Vliet et al., 2013), while the results show no consistent pattern of impacts of CV&C on power plants with closed-cycle cooling system. Country-level results show that about 31 countries were identified to have a consistent pattern of increase in hydropower production, while individual results from the reviewed study projected a consistent decline in 50 countries around the world.

4. Discussion

4.1. Summary of the body of evidence

This systematic scoping review was performed to examine the typology, extent and results of existing research conducted on CV&C impacts. To the authors' knowledge, this is the first scoping review to systematically assess both the current state of literature on CV&C impacts on energy system at a global level. At the regional level, the results showed a consistent increase in energy demand due to impacts of CV&C for the Americas, Africa and Asian continent (except for commercial sector in Central/North Asia and Eastern Asia by end of 21st century). Consistent decrease in energy demand was found in Northern and Eastern Europe, while increase in residential demand was projected in Oceania regions. In terms of energy supply technologies, consistent decrease in thermal power plants output were projected in Northern America, parts of Africa, across Asia, Oceania and Europe. Renewable energy technologies such as solar PV showed a robust consistent pattern of increase in the Caribbean and Central America, Northern and Southern Africa (by near century), and in Oceania regions from the near to end of the 21st century.

The reviewed studies agree on the pattern of global temperature increase, but inconsistent precipitation pattern. This is projected to increase energy demand for cooling, while commercial buildings will be more affected than the residential buildings due to contribution from internal heat loads (e.g. office equipment). Although this might be specific to some regions, Auffhammer and Aroonruengsawat (2011) concludes that cooling requirement for residential buildings are higher than commercial sector. This is because the influence of outdoor temperatures is lower compared to contributions from internal heat loads in commercial buildings which closes at night, compared to residential buildings were outdoor temperature and internal heat loads contributes to increase in cooling requirement for a larger part of the day. The consumption will be higher during summer night when climate change increases demand for cooling in the residential homes compared to commercial buildings (Seljom et al., 2011). Globally, studies show that heating demand fuel (e.g. natural gas) will decline while cooling demand fuels (e.g. electricity) will increase. In some temperate regions, this will be due to warmer summer (Parkpoom and Harrison, 2008), while colder regions will have an overall decrease in energy demand due to warmer winter and reduced requirement for heating (Wang et al., 2010).

The results also highlight the vulnerability of hydropower plants to CV&C as precipitation patterns are projected to change across the world. Most projections show an increase in hydropower generation during winter months and reduction during summer months. The decrease during the summer is due to factors such as peak air-conditioning demand (Hamlet et al., 2010) and climatic factors such as decrease precipitation and increasing temperature which leads to greater evapotranspiration (Oni et al., 2012). The decrease in precipitation results in decrease streamflow and reduced utilisation capacity, hence hydropower potential (Aronica and Bonaccorso, 2013). In some

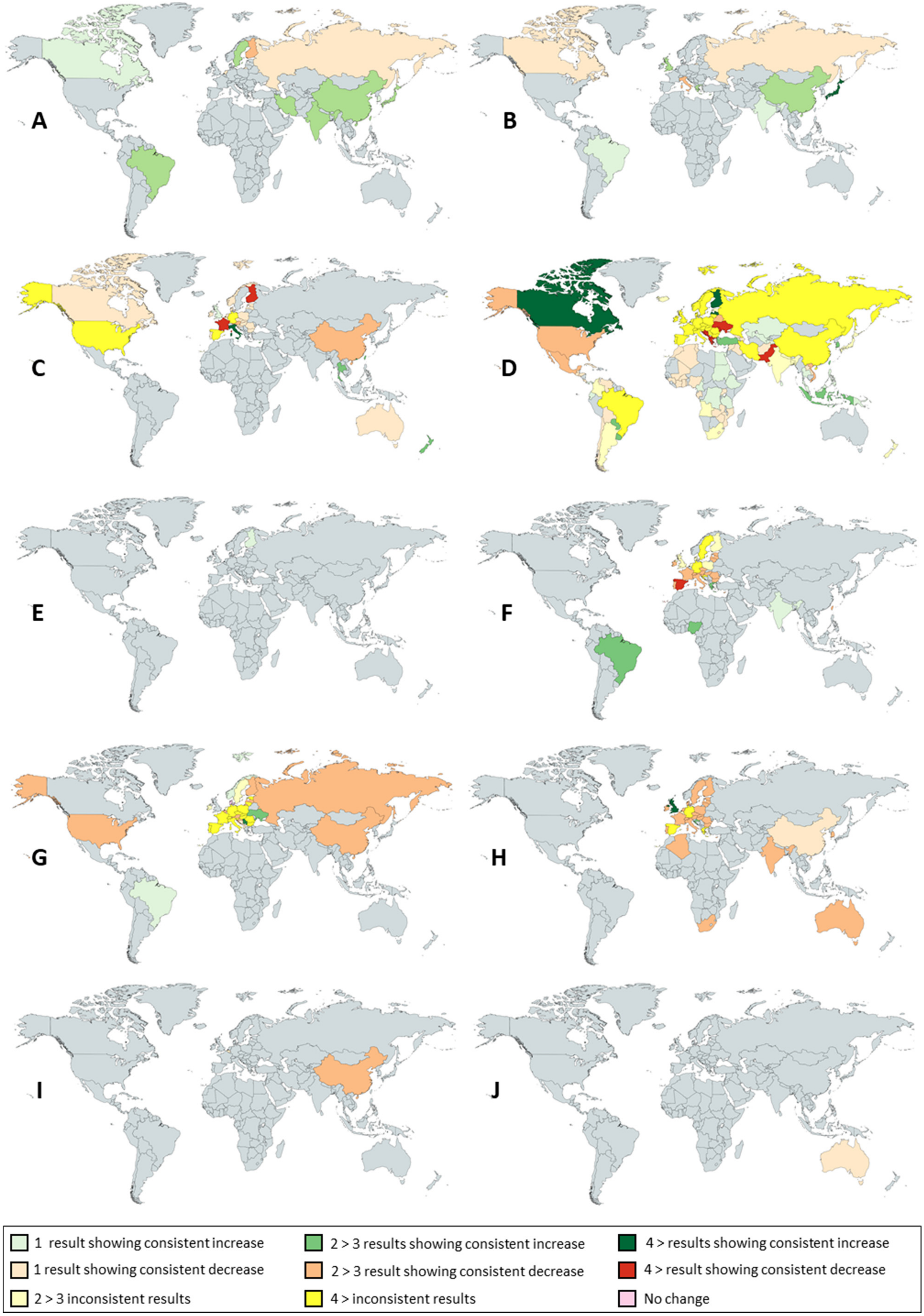

Fig. 9. Annual patterns of impacts of CV&C-ES for NT-MC (A: Residential, B: commercial, C: economy, D: hydro, E: bioenergy, F: wind, G: thermal, H: solar, I: wave, J: T&D).

regions, the loss in hydropower potential during summer months can be compensated by increased precipitation during winter periods (Carless and Whitehead, 2013). Similarly, the operation of thermal power plant relies on the availability of cooling water to condense steam from the turbine exhaust and cool the system. A potential impact of CV&C is the reduction of thermal power generation due to lower river discharge (from lower precipitation pattern) and higher river temperatures (Popescu et al., 2014).

4.2. Implications from the review

The findings from the reviewed studies show that changes in temperature will have important implication on energy demand for cooling and heating, reduction in efficiency of thermal power plant and significant changes in wind and hydropower production. This will also result in significant changes in electricity market as electricity companies and power distribution networks will have to upgrade their facilities to accommodate the changes due to global warming. As energy demand is projected to decrease in Northern Europe and increase in Southern Europe due to changes in heating and cooling demand, the power supply system will also be impacted upon. The impact on power supply system will be based on changes in the electricity supply priorities and impacts of CV&C on power output such as power plant efficiency.

In countries or regions where power supply from thermal power plant is projected to be affected tend to have power output from renewable sources increase (e.g. wind and hydropower in Northern Europe, Brazil and India, among others). An important implication for such differences could be a results of price differentials which will give incentives to boast power transmission from regions of lower demand to regions of higher demand. Also, there will be an added incentive to invest in generation capacity expansion in regions or countries projected to have higher energy demand than others with projected decrease in energy demand. However, it's unclear how these changes will shape the future energy system in different countries and regions, but the progressive view is a future where fossil fuel is phased out and replaced with renewables.

Advancing towards a renewable and sustainable energy system despite the looming climate change conditions will require power companies to incorporate climate change when building, redesigning or expanding power generation capacity. However, the literature reviewed show a dearth of guidelines specifying how power companies can incorporate changes during capacity expansion, especially in the case of hydropower plants (Lumbroso et al., 2015). Although in developed countries, the guidelines to safe-guard future energy technologies may be available, this information is lacking in some developing countries. Also, if the guidelines are available, the required skills might be quite challenging. Therefore, it is vital for power companies and policymakers to work together with other stakeholder to improve on planning, design and redesign, and operations of power plants to withstand future climatic conditions and avoid maladaptation to climate change.

4.3. Potential mitigation and adaptation measures

Combating climate change will require the collaborative efforts of building designers, owners and the government. A simple method for building owners is to adjust the thermostat to use higher cooling setpoint during summer and lower heating setpoint temperatures during winter (Waddicor et al., 2016). Building designers can increase insulative index of the glazing material to enhance solar heat gain and envelope insulation for exterior walls and roofs requirement to reduce envelope loss (Huang and Hwang, 2015; Karimpour et al., 2015). A flexible ventilation system such as the displacement ventilation and underfoot air distribution system can improve air flow pattern in buildings, reduce ventilation load and building energy consumption (Wang and Chen, 2014). Government policies such as the European Union initiatives on near zero energy buildings, provision and economic incentives for refurbishment of older buildings can reduce expenditures, mitigate the increase in GHG emissions and contribute towards adaptation since energy efficient buildings are less vulnerable to CV&C impacts (Zachariadis and Hadjinicolaou, 2014).

Furthermore, appliance efficiency improvement in residential buildings and adjustment of heating, ventilation and air conditioning system (HVAC) operational hours in commercial buildings has the potential to offset projected increase in energy demand due to climate change and this can be effective when coupled with supply-side strategies (Reyna and Chester, 2017; Wang et al., 2017). On the supply-side, hydropower dams should be designed to accommodate sufficient capacity to take advantage of higher winter flows (Park and Kim, 2014), but should not be oversized for actual inflow as indicated by Gaudard et al. (2013). However, expansion or construction of new storage capacity for dams and reservoirs could modify the natural landscape which may affect aquatic life and may not be acceptable by local communities. In this case, promoting renewable electricity as a global/long-term objectives may be in conflict with protecting aquatic ecosystem as a local/short-term objectives (Maran et al., 2014).

The expansion of dams to accommodate increased inflow may not necessarily result in more hydropower generation. This is because during period of extreme precipitation, reservoirs are forced to spill water without power generation to avoid overloading the dam structures. During the following summer months, reservoir drops to lower levels with low power generation, hence no advantage is gained from increased precipitation (Tarroja et al., 2016). Strategies for adaptation includes increasing hydropower plant efficiency to 10% to mitigate mean annual impacts of increased water constraints under climate change Van Vliet et al. (2016). For thermal power plants, measures include changing the cooling system of power plants from once-through to a closed-circuit or dry cooling system which is shown to be more robust to the effects of CV&C and declining flows due to human activities such as irrigation (Koch et al., 2012; Van Vliet et al., 2012).

4.4. Gaps in the literature review

This systematic scoping review shows that despite the growing body of literature examining the impacts of CV&C, there appear to be important gaps in the literature. Studies have considered the impact of climate change on air conditioner penetration; however, few studies have examined the considerable changes in efficiency improvement and market saturation of other heating and cooling technologies in future periods. The studies reviewed assume a constant load factor and energy demand pattern, but future climatic conditions may alter consumer or occupant behaviour. Therefore, future studies need to account for changes in occupant behaviours in buildings. Few studies considered the effect of price change, but the authors found no study examining price change due to improvement in energy efficiency under climate change. Even fewer studies analysed the risk of new adaptative building design strategies utilising natural energy flows in air materials.

Little assessment of the direct and indirect impact of climate change on hydropower generation. This includes environmental implication (e.g. extreme events), possible damages associated with hydrologic changes and shutting down hydropower plant due to floods. The authors found no study exploring the effect of glacial melt on summer low flows, late summer and ground water recharge on hydropower production. Glacier melting will become relevant in regions where glaciers are going to disappear in the next decades. This is the case for South America (high impact for Peru) and in some parts of the European Alps. This will have severe consequences for major electricity supply companies in countries such as Iceland where projections show a 25% decrease in glaciers volume from 2000 to 2050 (Sveinsson, 2015). This will result in increased runoff on hydropower production capacity, hence, require an increase or redesign of its power generation, transmission and distribution system as global warming becomes more

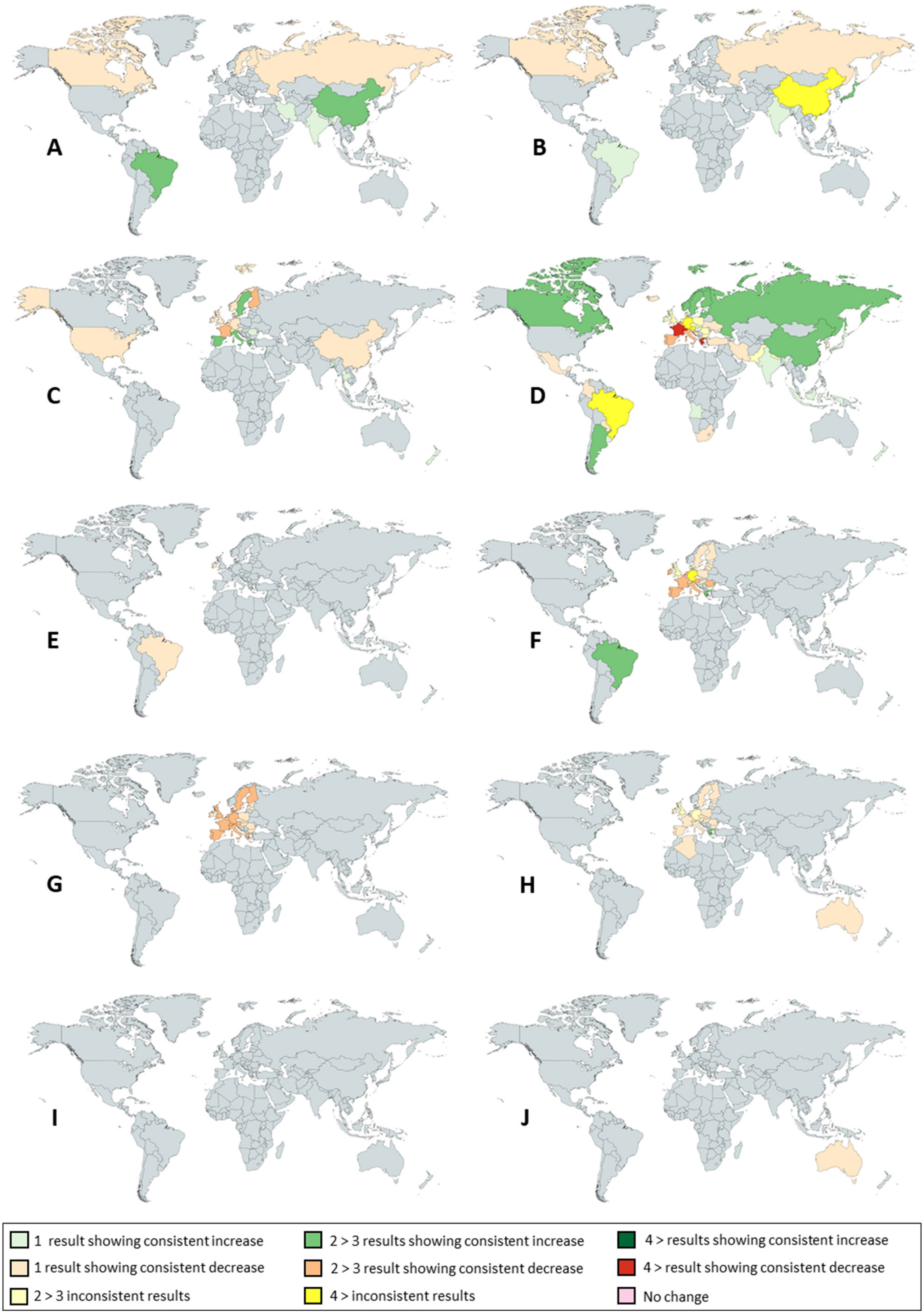

Fig. 10. Annual patterns of impacts of CV&C-ES for EC (A: Residential, B: commercial, C: economy, D: hydro, E: bioenergy, F: wind, G: thermal, H: solar, I: wave, J: T&D).

intense. However, recent studies such as Schaefli et al. (2019) examined the role of glacier retreat for Swiss hydropower production and showed that reduction in production from 2040 to 2090. Therefore, it may be interesting to identify how strong the dynamic interaction will be between global warming, glacier melt and hydropower production in the coming decades.

Articles explored the impact of CV&C on cooling water availability, but to the author's knowledge no study considers current and future configurations of thermal power plant cooling equipment. Fewer studies examined the impact of CV&C on T&D infrastructure and even fewer studies have considered the cost implication of improving the transmission grid (e.g. direct current transmission lowers T&D losses) and applying mitigation options to reduce the impact of rising temperatures. Other limited studies include studies investigating thermal power plant emissions under climate change, applying fixed emission factors and linking emissions back to the GCM data.

For wind energy technologies, the impacts of CV&C on offshore wind potential was the least explored in the literature review. Few studies on solar PV considered the impact of CV&C on solar cells or PV materials and how future solar radiation might affect adjustable or fixed tilt angles of solar panels. Adaptation and mitigation measures applied in the literature on CV&C impacts has not fully qualified the costs and benefits of each measures to the energy system. Also, technological innovation for future energy technologies is not considered in the reviewed studies. Assessment should examine cross-sectoral linkages, back-loops and include a complete climate system assessment model with more realistic representation of sea ice, ocean and ecosystem responses.

Also, the integration of supply side impacts with demand side impacts should consider socioeconomic dynamics (e.g. effects on population density reflecting climate-related migrations). The current studies can be improved by considering the implications of long-term effects of CV&C on an optimised energy system. Finally, the studies reviewed showed that despite the advancement of the knowledge frontier, there are still sparse studies on CV&C impacts in developing countries and uneven impact assessment of energy technologies. These technologies include bioenergy, wind, thermal, solar, wind and wave energy, while limited studies addressed CV&C impacts on T&D networks. Also, there are more near to middle century studies compared to end of the 21st century impact assessment literature.

Finally, the reviewed studies placed little emphasis on the implications of uncertainties associated with climate change model projections and its importance or acceptability to the wider audience. In other words, previous studies have not fully bridged the gap between uncertainties and communicating the results to inform on planning, adaptation and mitigation strategies. Therefore, it is essential for future studies focusing on the impact of CV&C on energy system to better communicate issues related to uncertainties in climate projections and improve the communication of results to the global audience. Addressing these research gaps will further advance the literature, provide options to protect the future energy system and increase our knowledge on CV&C impacts on the energy system in the coming years.

4.5. Strengths and limitations of the systematic scoping review

This scoping review applied rigorous and transparent approach. It follows a protocol reviewed by the research team with expertise in literature synthesis and scoping reviews. A broad search of the literature was conducted using two electronic search databases and one internet search engine and snowball technique. Screening the articles and data characterisation forms were pretested by the reviewers, while the articles were independently reviewed by the reviewers who regularly met to resolve conflicts. To ensure consistency in the scoping review which was conducted in a systematic manner, the Endnote software was used to manage and account for all citations retrieved from various databases. An updated search was conducted in December 2018 to ensure inclusion of recent publications.

This scoping review has several limitations. First, the searches were limited to articles published in English, potentially resulting to language bias and exclude relevant studies published in other languages. Second, the CV&C are associated with terms such as temperature change and weather conditions, which may have excluded terms such as overheating, extreme weather and global warming. Third, the search engines used are multidisciplinary databases, but other databases may contain additional studies relevant to this review. Fourth, subject experts or researchers were not contacted for additional studies and studies from gray literature were not included. Finally, scoping reviews are not meant to assess the quality of the literature assessed or in this study, the quality of the GCMs used for CV&C impact assessment. However, the eligibility criteria ensured that the studies included for the review applied projections from relevant GCMs used for CV&C impact assessment. Therefore, this scoping review provides a comprehensive overview on the impact of CV&C on the energy system at a regional and country scale, reporting >1790 individual results from 153 studies out of 176 articles included for the review.

5. Conclusions

The impacts of CV&C on future energy system have received considerable attention over the past decades. This systematic scoping review collated and mapped evidence by identifying consistent pattern of impacts based on results from studies reviewed. Although this review identified robust pattern of CV&C impacts, there is areas requiring further research. Future literature review should apply either a systematic or scoping review approach to contextualise the results in terms of technological, economic and environmental aspect. Technological research can examine the implication of CV&C on future energy system in terms of changes in energy demand pattern in relation to changes in energy supply mix (both fuel mix and technology switching). The cost dynamic implications which includes social cost, changes in sales revenue, investment cost of capacity expansion and cost-benefit analysis can be included in economic assessment. The environmental aspect should explore the changes in GHG emissions under future climatic conditions.

The findings from the review agree that temperature changes will have serious implications on the energy system which will lead to changes in energy demand and energy supply. On the demand side, each temperature rise is projected to increase peak energy demand by 0.45%–8.5% due to increase in AC use. This will result in an increase in expenditure for consumers and increase in GHGs from peaking power plants which are mostly fossil fuel based. On the supply side, climate impact had less impact on solar PV systems compared to other renewables. This implies that solar PV system are more resilient to in a world of increasing uncertainty and vulnerability of the energy system to CV&C impacts. Therefore, solar PV system will have an important role to play in mitigating GHG emissions and adapt the energy system to future climatic conditions.

Further, thermal power plant in most regions may experience a decline in production efficiency due to global warming which will decrease the availability of cooling water for thermal plant operation. On water availability, the hydropower plant may also experience either a shortfall in power output due to reduced rainfall (most part of Africa and Asia) or increased power production due to glacier melt in other regions (e.g. Northern Europe). However, the increase in glacier melt may result in flooding in countries located in Norther Europe which may not translate to increase in power production from hydropower stations. These changes in power supply and demand will lead to significant changes in the electricity market as power companies will have to make changes in generation capacity, transmission and distribution networks.

In countries with interconnected electricity markets, the impact of CV&C on fossil fuel power plant and increase energy demand may make a case for renewable energy technologies such as hydropower and solar which is projected to increase in some regions. Where such

Table 2
Detailed results of pattern of CV&C impacts on the energy system from the reviewed studies.

Sector/energy source	Consistent pattern				Inconsistent pattern		No change
	Increase		Decrease				
	Regional	Country	Regional	Country	Regional	Country	Regional/Country
Energy demand							
Residential demand	Southern Europe (#80 EC:1), Asia (#20 NT-MC: 5, EC: 5), Americas (#20 NT-MC: 4, EC: 4), Oceania region (#20 NT-MC: 1, EC: 1)	Brazil (6 results), Canada (NC: 1 result, EC: 1 result), Hong Kong (4), China (5), Cyprus (NC: 1, EC: 1), India (4), Iran (3), Japan (NC: 2), South Korea (NC: 1), Sweden (NC: 1), Taiwan (3)	Northern Europe (#32 NT-MC: 1), Western Europe (#32 NT-MC: 1; #80 NT-MC: 1, EC: 1)	Finland (3), Netherlands (MC: 1), Russia (MC: 1, EC: 1), Sweden (EC: 1)	Southern and Eastern Europe (NC-MC: 4)	Sweden (MC: 2)	
Commercial demand	Southern Europe (#80 EC:1), East Asia (#20 NC-MC:1), Southern, Western, Southeastern Asia (#20 NC-MC: 3, EC: 3), the Americas (#20 NC-MC: 4, EC: 4)	Brazil (3), Hong Kong (6), China (NC: 1, EC: 2), Greece (3), Japan (5)	Northern Europe (#32 NT-MC: 1; #80 NT-MC: 1, EC: 1), Western Europe (#32 NT-MC: 1; #80 NT-MC: 1, EC: 1), Central Asia (#20 NT--MC: 1, EC: 1), East Asia (#20 EC: 1), Oceania region (#20 NT-MC: 1, EC: 1)	Canada (MC: 1, EC: 1), Italy (NC: 1, MC: 1), Russia (MC: 1, EC: 1)	Southern, Eastern Europe (NC-MC: 4)		Eastern Europe (EC: 1)
Building demand	Africa (#65 EC-MC: 4, EC: 4), Asia and Americas (#20 NC-MC: 9, EC: 9), Oceania (#20 NC-MC: 1)	Bulgaria (MC: 1), Greece (EC: 2), Italy (8), New Zealand (3), Ireland (MC: 1, EC: 1), Luxembourg, Netherlands, Norway (MC: 3, EC: 3), Poland (MC: 1), Portugal (MC: 1), Romania, Slovakia, Slovenia (MC: 3), Spain (NC: 2, EC: 2), Taiwan (3), Thailand (3), Sweden (EC: 2), United Kingdom (MC: 1, EC: 1)	Northern Europe (#32 NC-MC: 1; #40 NC-MC: 1, EC: 1; #65 NC-MC: 1, EC: 1), Eastern Europe (#65 NC-MC:1, EC: 1), East Asia (#20 EC: 1), Oceania (#20 EC: 1)	Australia (4), Belgium (MC: 1, EC: 1), Canada (MC: 1), China (3), Croatia, Czech Republic, Denmark, Estonia, Hungary, Latvia, Lithuania (MC: 7), Finland (5), France (7), Germany (EC: 1), Portugal (EC: 1), Sweden (MC: 1), USA (EC: 1)	Southern and Western Europe (NC-MC: 4, EC: 4)	Germany (5), Spain (3), Switzerland (6) and USA (5)	
Energy supply							
Hydropower	Northern Europe (#66 NC-MC: 1, EC: 1; #125 NC-MC: 1, EC: 1; #128 NC-MC: 1, EC: 1; #132 NC-MC: 1), East Africa (#46 NC-MC: 1; #128 NC-MC: 1, EC: 1; #132 NC-MC: 1), Central Africa (#46 NC-MC: 1), Eastern, Southern and Southeastern Asia (#46 NC-MC: 1; #132 NC-MC: 1; #128 NC-MC:1, EC: 1), Northern America (#46 NC-MC: 1; #132 NC-MC: 1)	Angola (MC: 2), Bangladesh (NC: 1, EC: 1), Cameroon (MC: 1) Canada (8), China (EC: 2), Democratic Republic of the Congo, Ecuador and Egypt (MC: 3), Estonia (EC: 1), Finland (9), Gabon (MC: 1), Hungary (EC: 1), Iceland (MC: 1), India (NC: 1, EC: 1), Indonesia (4), Ireland (EC: 4), Japan (NC: 1, EC: 1), Latvia (8), Lithuania (EC: 1), New Zealand (NC: 2, EC: 1), Norway (EC: 2), Russia (MC: 2, EC: 2), South Korea (5), Sweden (EC: 3), Taiwan (3), Kazakhstan, Kenya and Kyrgyzstan (MC: 3), Malaysia (MC: 1), Panama, Papua New Guinea, Philippines (MC: 3), Sri Lanka, Sudan, Tajikistan, Tanzania, Uganda (MC: 5) and Uruguay, Uzbekistan (MC: 3)	Southern Europe (#66 EC: 1; #125 EC: 1; #128 EC:1), Eastern Europe (#66 NC-MC: 1, EC: 1; #80 NC-MC:, EC: 1; #128 NC-MC: 1, EC: 1; #133 NC-MC: 1), Northern Africa (#46 NC-MC: 1; #128 NC-MC: 1, EC: 1; #132 NC-MC: 1, EC: 1), Southern Africa (#46 NC-MC: 1; #121 NC-MC: 1, EC: 1; #128 NC-MC: 1, EC:1; #132 NC-MC: 1, EC: 1), Central and Western Asia, the Americas (#128 EC: 6)	Afghanistan, Algeria and Australia (MC: 3), Albania (6), Angola (NC: 1), Argentina (NC: 1), Belarus (NC: 2, MC: 1), Bosnia-Herzegovina (6), Brazil (NC: 7), Burkina Faso (NC: 1), Colombia (NC: 2, EC: 1), Costa Rica (MC: 1), Croatia (9), France (MC: 4, EC: 4), El Salvador (MC: 1), French Guiana, Georgia, Ghana, Guatemala, Guinea, Honduras, Italy, Ivory Coast, Laos, Lesotho, Mali, Mozambique, Morocco (MC: 13), Greece (NC: 5, EC: 4), Iceland (NC: 1, EC: 1), Iran (EC: 1), Italy (EC: 3), Luxembourg (MC: 2, EC: 2), Macedonia (6), Moldova (NC: 2, MC: 2), Montenegro (NC: 1, MC: 3), Pakistan (NC: 1, MC: 2), Portugal (EC: 3), Paraguay (MC: 2), South Africa (NC: 1, EC: 1), Spain (NC: 4, EC: 3), Switzerland (EC: 4), Togo, Tunisia (MC: 2), Turkey (3), Ukraine (5), Vietnam (NC: 1, MC: 1), Venezuela, Zambia, Zimbabwe (MC: 3)			
Bioenergy		Finland (NC: 1)		Brazil and Ireland (EC:			

Table 2 (*continued*)

Sector/energy source	Consistent pattern				Inconsistent pattern		No change
	Increase		Decrease				
	Regional	Country	Regional	Country	Regional	Country	Regional/Country
production				2)			
Wind power plants	North Europe (#14 EC: 1; #125 EC: 1), northern and western part of Mediterranean Sea, Black Sea (#63 NC-MC: 3), Baltic Sea (#14 NC--MC: 1, EC: 1), South Africa (#33 NC-MC: 1)	Brazil (4), Greece (5) and India (NC: 1)	South and Western Europe (#14 EC: 2; #125 EC: 2), all parts of the Mediterranean Sea (#41 NC-MC: 1; #63 NC-MC: 3, EC: 4), Black Sea (#63 EC: 1), Northern Africa (#41 NC-MC: 1)	Austria (5), Belgium (NC: 1, MC: 1), Bulgaria (3), Cyprus (3), Czech Republic (3), Denmark (NC: 1), Estonia (3), Finland (MC: 1, EC: 1), France (5), United Kingdom (NC: 1, MC: 1), Hungary (3), Ireland, Italy (10), Latvia, Lithuania, Luxembourg (9), Netherlands, Poland (NC: 2, EC: 1), Portugal, Romania, Spain (15), Slovenia (3), Sweden (NC: 1, EC: 1), Switzerland (3), Taiwan Strait (3)	Northern and Southern Europe (NC-MC: 6) and Eastern Europe (NC-MC: 3, EC: 3)	Belgium (EC: 1)	
Thermal Power plants	Eastern Asia (#150 EC: 1), Southeast Asia (#132 NC-MC: 1; #150 NC-MC: 1)	Italy (NC: 1) and Serbia (NC: 2, MC: 1)	Southern Europe (#32 NC-MC: 1; #80 NC-MC: 1, EC: 1; #131 NC-MC: 1; #132 NC-MC: 1; #133 NC-MC: 1, EC: 1), Western Europe (#32 NC--MC: 1; #40 NC-MC: 1, EC: 1; #80 NC-MC: 1, EC: 1; #131 NC-MC: 1; #132 EC: 1), Eastern Europe (#32 NC-MC: 1; #80 NC-MC: 1, EC: 1; #132 NC-MC: 1; #132 NC-MC: 1; #133 NC-MC: 1, EC: 1), Western and Southern Africa (#132 NC--MC: 2, EC: 2), Central, Southern and Western Asia (#132 NC-MC: 4; #150 NC-MC: 4, EC: 4), North America and Oceania regions (#132 NC--MC: 2, EC: 2; #150 NC-MC: 2, EC:2)	Australia (NC: 1, EC: 2), Belgium (EC: 1), Bosnia-Herzegovina (MC: 1), Brazil (NC: 1), Bulgaria (EC: 1), China (NC: 1, MC: 1), Croatia (4), Czech Republic and Estonia (EC: 2), Finland (3), France, Germany (EC: 4), United Kingdom (EC: 3), Greece (EC: 2), Hungary (EC: 1), Ireland (NC: 1, EC: 1), Italy (EC: 2), Latvia (3), Lithuania, Poland, Romania, Slovakia, Slovenia (EC: 5), Netherlands (EC: 2), Norway (MC: 1), Macedonia (MC: 1), Montenegro (MC: 1) Portugal (EC: 4), Russia (NC: 1, MC: 1), Spain (EC: 2), Sweden (NC: 1, EC: 2), Switzerland (EC: 2) and USA (3)	Northern Europe (NC-MC: 5, EC: 2) and Southeast Asia (EC: 2)	Estonia (NC: 2)	North, East and Central Africa (#132 NC-MC: 3, EC: 3), Central and South America, the Caribbean and Oceania regions (#132 NC-MC: 4, EC: 4; #150 NC-MC: 4, EC: 4)
Solar photovoltaic	Southern Europe (#51 EC: 1), North Africa (#48 NC-MC: 1), South Africa (#33 NC-MC: 1), Central America, the Caribbean and Oceania (#22 NC--MC: 3; EC: 3; #48 NC--MC: 3; #146 NC-MC: 3)	Croatia (3)	Northern, Southern, Western and Eastern Europe (#32 NC-MC: 4; #51 EC: 3), Central, East and Western Africa (#48 NC-MC: 3), Asian region (#48 NC-MC: 5; #146 NC-MC: 5) and South America (#22 EC:1)	Algeria (5), Australia (5), Austria, Bulgaria (6), Belgium, China (NC: 2), Cyprus, Czech Republic, Estonia (9), Denmark (NC: 1, MC: 1), Finland (3), France (3), United Kingdom (NC: 1), Hungary (3), India (2 for NC and MC), Ireland (NC: 1, MC: 1), Italy (3), Latvia (3), Lithuania (3), Netherlands (3), Poland (3), Portugal (3), Romania (3), Slovakia (3), South Africa (NC: 1, MC: 1), Spain (EC: 1), Sweden (3) and Switzerland (3)	South America (NC-MC: 3)	Germany (10), United Kingdom (EC: 2), Greece (6) and Spain (4)	North America (#146 NC-MC: 1)

Coding interpretation: '#xy' number identifies an article included for the quantitative review which is available in Table S2b in Supplementary File 2; the NC, MC and EC means near century (2010–2039 or 2030s), mid-century (2040–2069 or 2050s) and end of century (2070–2099 or 2080s), respectively; ':xy' numbers denotes the number of individual results from a particular article which is shown on the right side of Table S2b in Supplementary File 2. Note that the quantification of increase and decrease in energy demand and supply from the articles reviewed and coded in Table 2 are based on percentage changes of more or less than ±1%. i.e. an increase <1% or decrease less than −1% is not considered a significant impact of climate change on energy demand or energy supply technologies presented in Table 2.

scenario exists, the implication will be differences in power prices which will give an added incentive for power companies to invest in sustainable power generation system. Besides renewable energy technologies, CCS for thermal power plant has been another option for GHG reduction but its application have raised a lot of questions due to its high cost compare to renewables. Some studies are of the opinion that CCS technologies are solution of the past and no longer necessary in a real progressive view of the future sustainable energy system (Breyer et al., 2018; Pursiheimo et al., 2018; Teske et al., 2018).

A better option may be the application of carbon capture and use (CCU) which not only captures the CO_2 but can potentially be used in manufacturing process (e.g. material for road construction). However, it remains unclear how changes in these low carbon technology options will shape the future energy system in the coming years considering climate change conditions. This aspect is still lacking in the literature and require further investigation. Other important areas of research include examining the impact of extreme weather events on future energy infrastructure, cross sectorial impacts of interconnected sectors, impacts on thermal and renewable power plants from a wholistic view considering inter-seasonal variations.

Future impact assessment should integrate the impact of CV&C on supply and demand side while consider socioeconomic dynamics. The study can also be extended to include cross-sectoral linkages and back-loops in a complete climate system model. Finally, future studies should examine how different international climate agreements and climate instruments might alter the energy markets under future climate conditions. As the global climate is changing in a future that is highly uncertain, the energy system is should also evolve. Policymakers, utility operators and researchers will continue to examine the pattern of CV&C impacts and explore mitigation and adaptation options for the energy system. This review could inform and safeguard energy infrastructure against climate change, ensure security of energy supply and ensure appropriate adaptation measures.

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